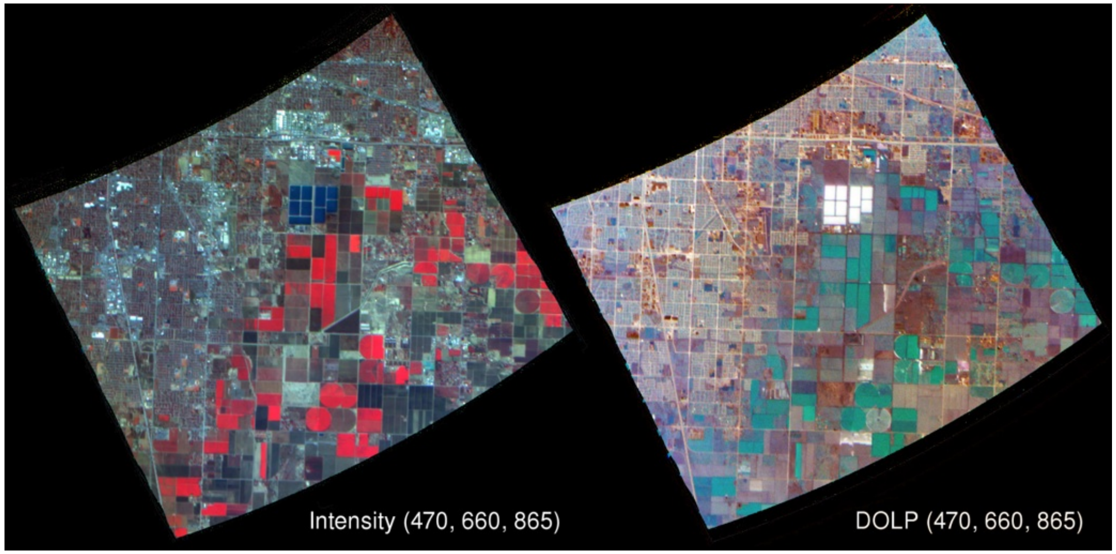
Status of Multiangle SpectroPolarimetric Imager (MSPI) technology development



ACE SWG   Greenbelt, MD   9-11 June 2014

David J. Diner
Jet Propulsion Laboratory, California Institute of Technology
and the MSPI Team

Objective

- Develop imaging polarimeter technologies suitable to meet requirements identified by the ACE Science Working Group for aerosol and cloud optical depth and microphysical property retrievals

- The envisioned instrument represents a fusion of MODIS, OMI, MISR, AATSR, POLDER, and APS capabilities

- The driving requirements include:
  - Multiple view angle imagery with sub-km spatial resolution
  - Swath width capable of 2 day coverage at (nadir), less frequently off-nadir
  - UV-SWIR spectral coverage
  - **Polarimetry in selected bands with uncertainty in degree of linear polarization (DOLP) of ±0.005**

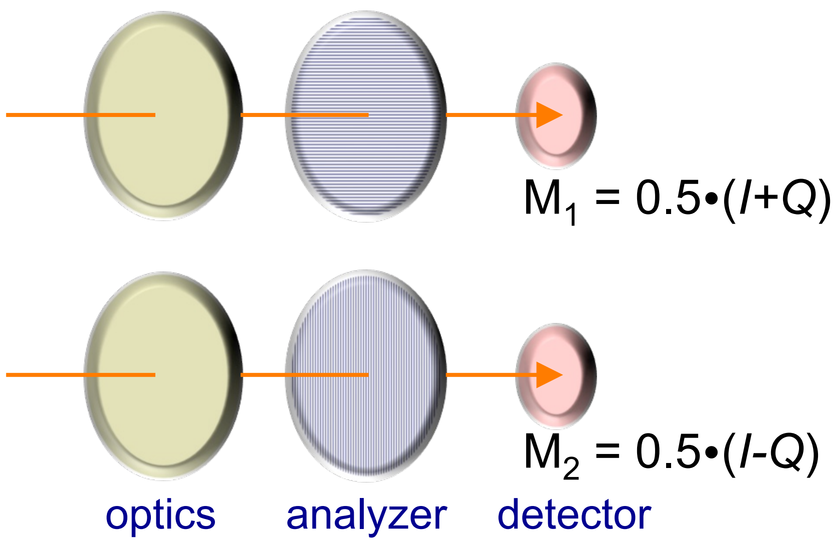
Polarimetry background

- Characterizing the radiation field requires measuring the Stokes components:
  - *I* is intensity
  - *Q* is preference for 0º over 90º polarization
  - *U* is preference for 45º over 135º polarization
  - Circular polarization *V* is negligible for natural Earth scenes

$$DOLP = [(Q/I)^2 + (U/I)^2]^{1/2} = [q^2 + u^2]^{1/2}$$

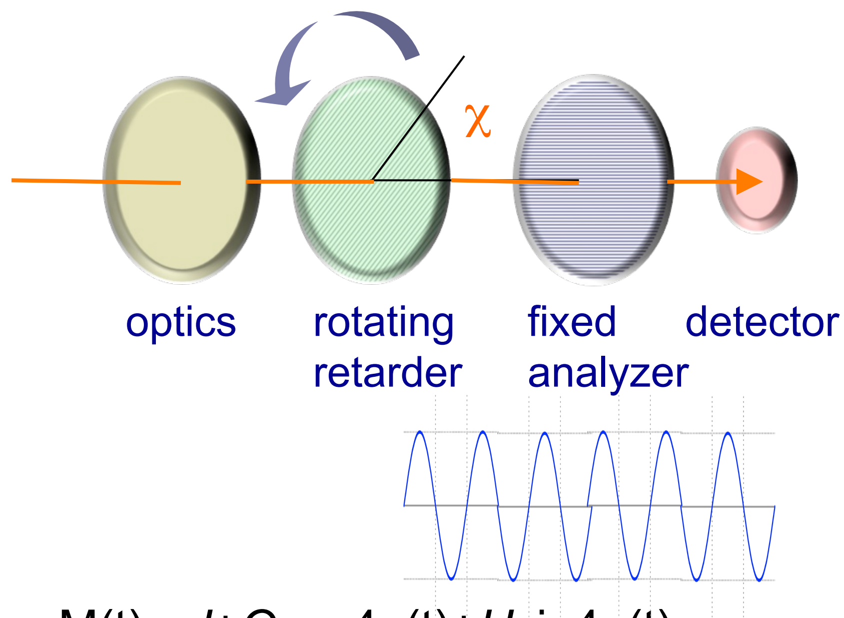
$$AOLP = 0.5 * \arctan(u/q)$$

- Polarization measurement typically uses a combination of *analyzers* and *retarders*



Similar system with analyzers at 45º and 135 measures *U*

Static



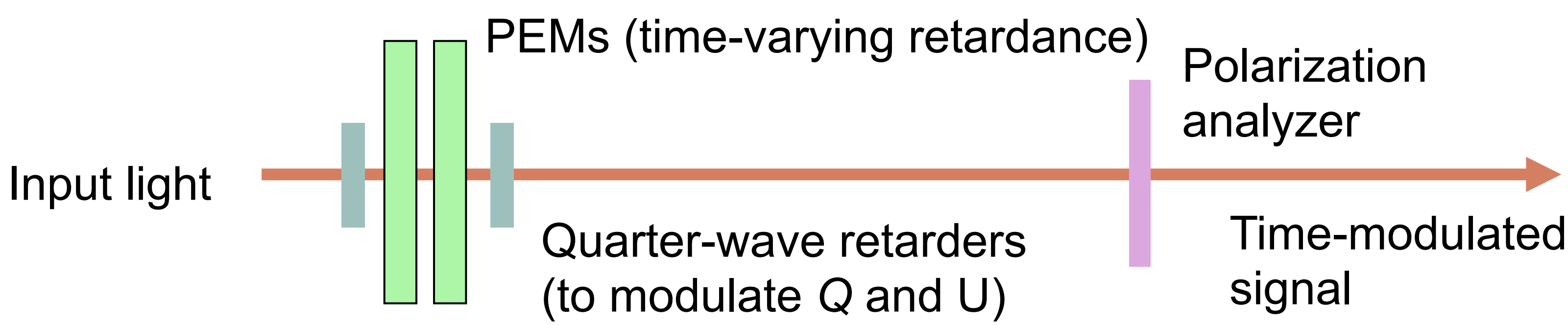
$$M(t) = I + Q\cos 4\chi(t) + U\sin 4\chi(t)$$

Modulated

Motivation for MSPI modulation approach

- “The most simple and stable modulators with the best optical properties are the piezoelastic [photoelastic] modulators (**PEMs**).”
  – Povel et al. (1990)

- “**Polarization modulation** is essential to accurate polarimetry in the optical region...one strives to modulate only the polarization preference, leaving the Stokes *I* sensitivity constant.”
  – Tinbergen (2005) *Astronomical Polarimetry*



- Measurements of *Q* and *I* share the **same optics and detector for each pixel** (similarly for *U* and *I*) enabling accurate imaging of degree of linear polarization (DOLP) as *relative* measurements

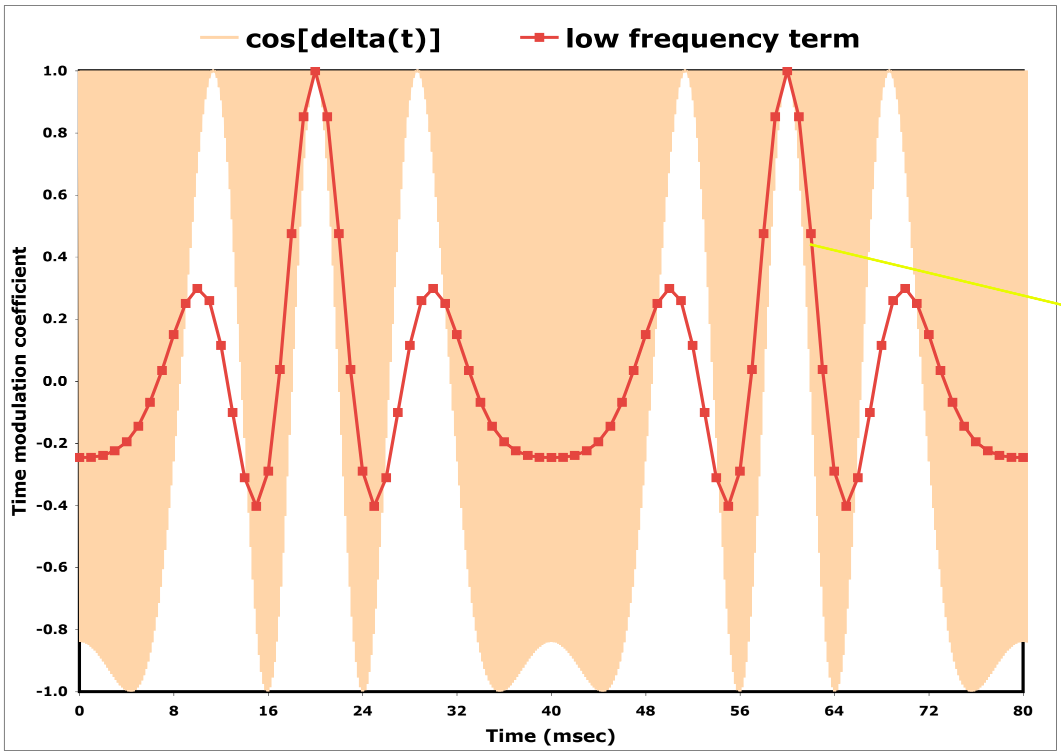
MSPI dual-PEM configuration

Typical PEM retardance modulation frequency is 42 kHz

This would require too rapid a readout of the imaging detectors and would introduce significant noise

MSPI solves this by putting 2 PEMs in series with slightly different frequencies to generate a slower 25 Hz beat signal

$\boxed{\delta_0 = 5}$

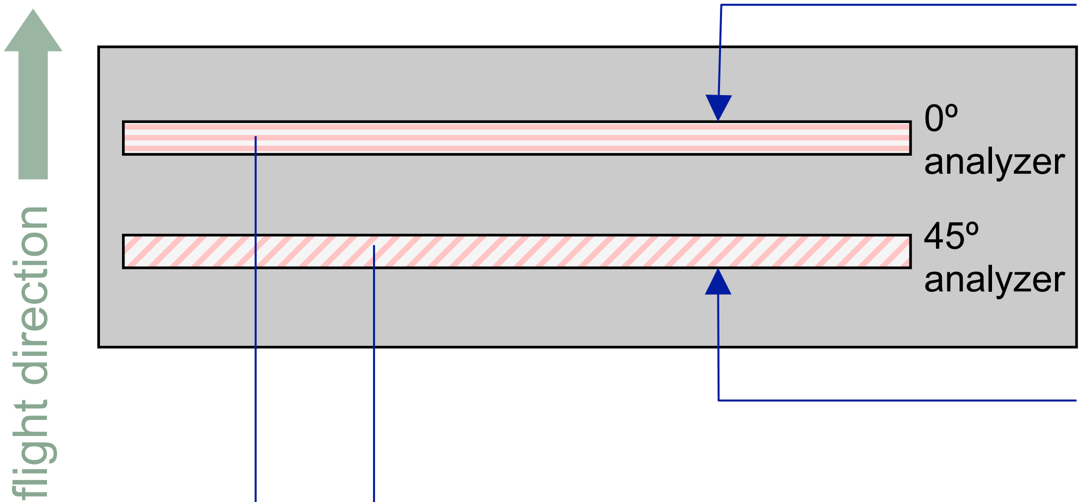


δ_0 = the retardance amplitude of each PEM (wavelength dependent)

Bessel function modulation F(t)

High frequency oscillation is averaged out

Polarimetry using dual-PEM temporal modulation



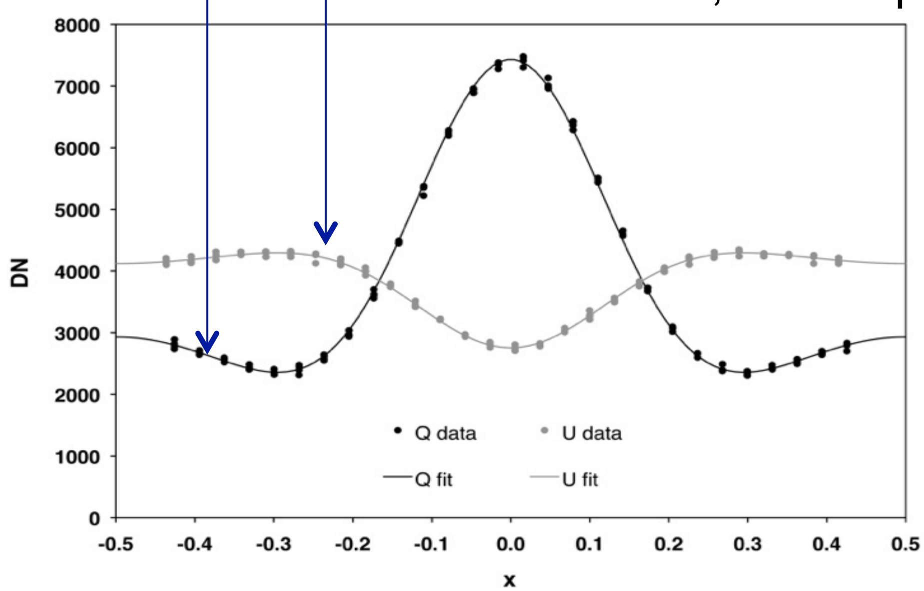
$S_0 = 0.5\,[I + Q \bullet F(t)]$

→ $q = Q/I$ from each pixel

$S_{45} = 0.5\,[I + U \bullet F(t)]$

→ $u = U/I$ from each pixel

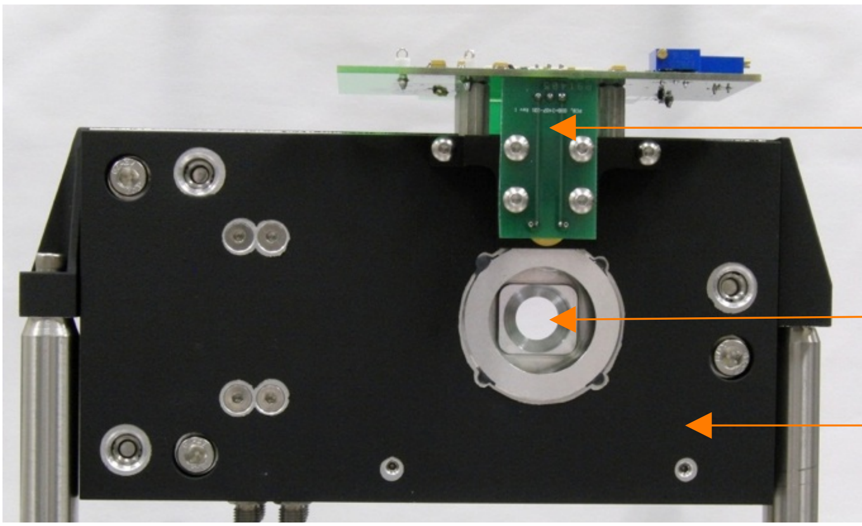
1 frame = 40 ms; 20 samples read out each frame



q and *u* are obtained as *relative* measurements independent of absolute radiometric calibration

Diner et al. (2007), (2010)

Dual PEM retardance modulator subassembly



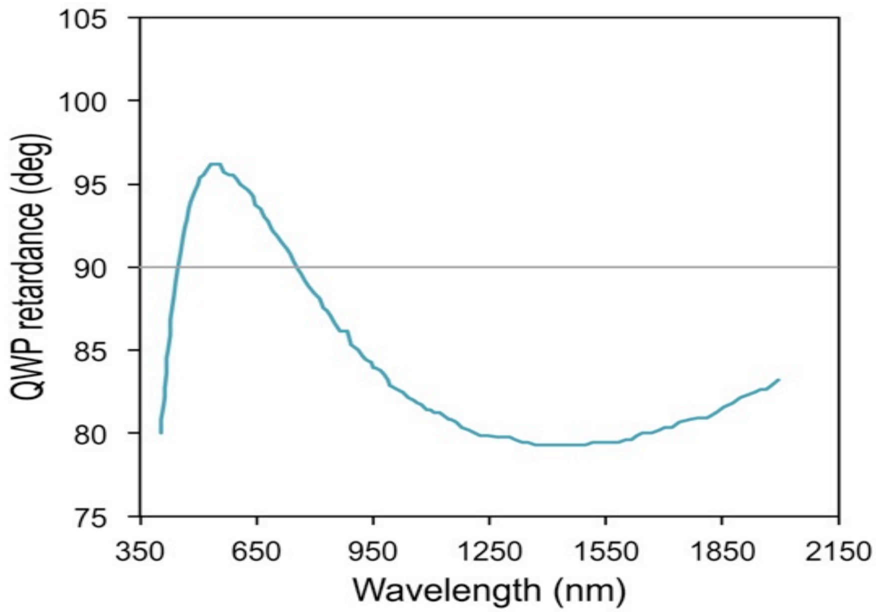
"Optical probe" uses LED probe beam to maintain constant PEM retardances

Aperture for imaging

Spaceflight qualified package

- A custom package with bonds engineered and built to spacecraft was vibrated in all three axes at 15 g RMS, covering ~90% of the acoustic loads experienced by instruments flown on Atlas-5 and Delta-IV launch vehicles with 3 dB margin
- PEM functionality was retested to verify that there had been no damage to the bond line holding the PEM head to the piezoelectric transducer
- PEM retardance stability was tested in the laboratory at a number of fixed set point temperatures from -30 °C to +50 ºC; it will be thermally stabilized in space
- A dual PEM has been operating in the lab nearly continuously for > 5.5 years

Achromatic quarter-wave retarder subassembly

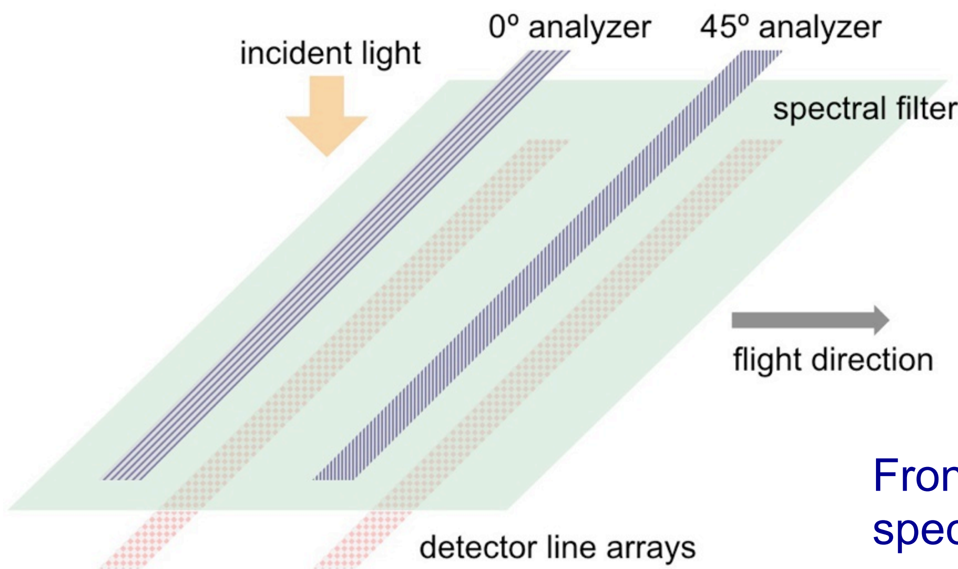


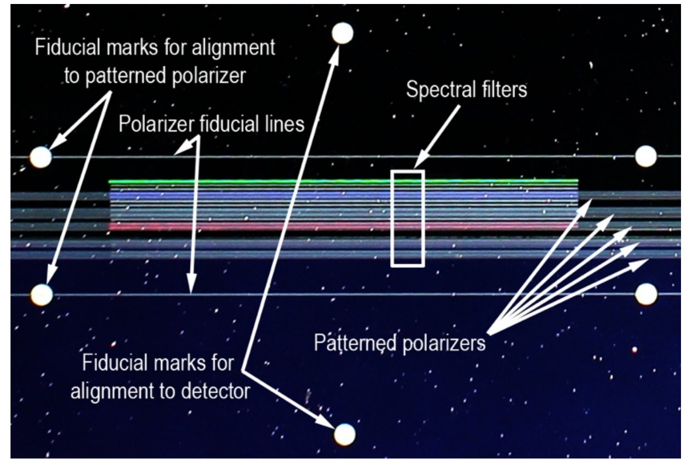
Fabrication methodologies for compound quartz:sapphire:MgF_2 retarder were developed

Retardance is within ±10º of ¼-wave (90º) from the blue to the SWIR

- ¼-wave retarders comprised of space qualified optical materials [quartz and sapphire: Galileo photopolarimeter, Solar-B Solar Optical Telescope waveplates; MgF_2: MISR Lyot depolarizer) have been built and used in operation between 0ºC and 20ºC
- A similar compound retarder for OCO-3 demonstrated survivability of the bonds through thermal cycling in vacuum between -20ºC and 35ºC
- Vibration testing of the OCO-3 article at 64 g in each axis showed no vibration-induced structural defects

Focal plane spectropolarimetric filter subassembly

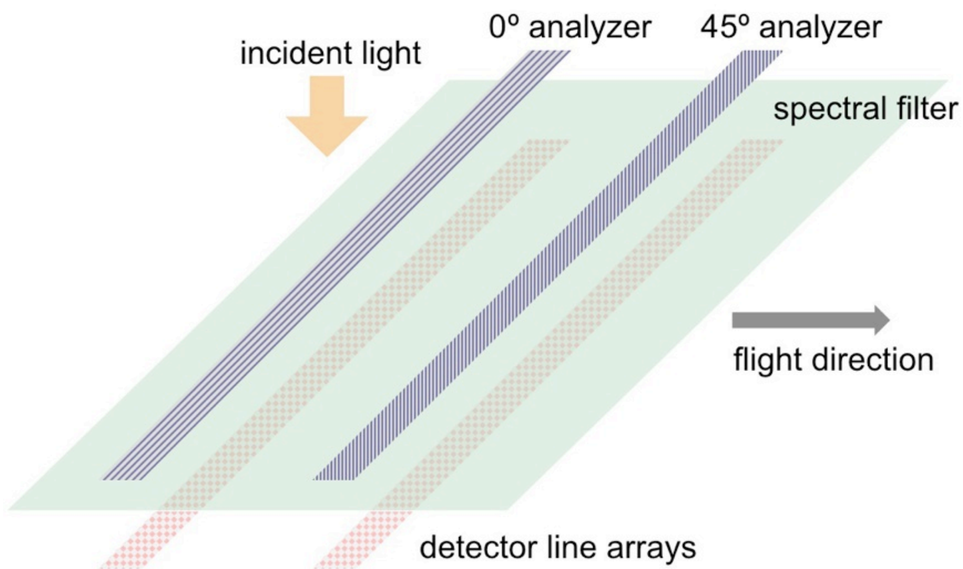




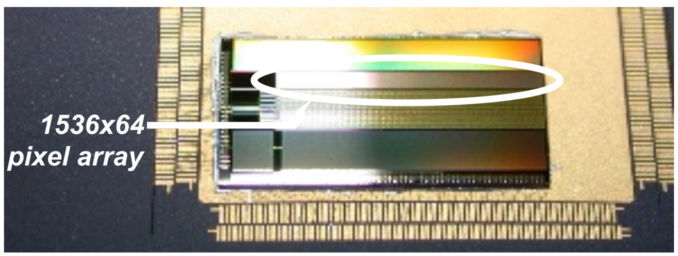
Front- and back-lit photograph of spectropolarimetric filter shows the stripe spectral filters and patterned polarizers

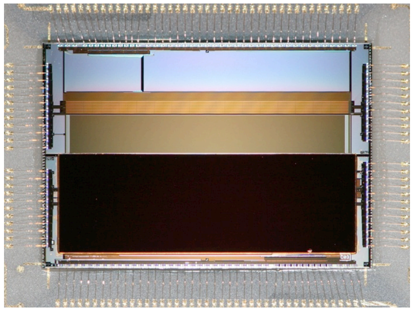
- The MSPI spectropolarimetric filters are “butcher block” assemblies of patterned wiregrid polarization analyzers and miniaturized stripe filters
- Structural replicates of the MSPI filters were run through thermal stress tests in vacuum, consisting of 123 thermal cycles between 220K and 313K and 108 additional cycles between 180K and 313K
- The tested filters survived thermal cycling and meet bondline integrity requirements with substantial margin

Focal plane readout integrated circuits and detectors

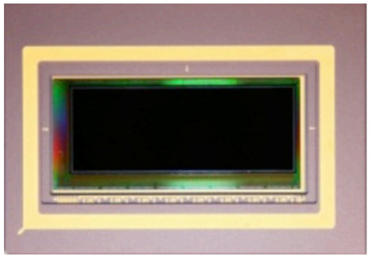


- Candidate detectors for MSPI are JPL-developed high-speed/ low noise devices or Teledyne's CHROMA imagers
- Both have been put through environmental testing



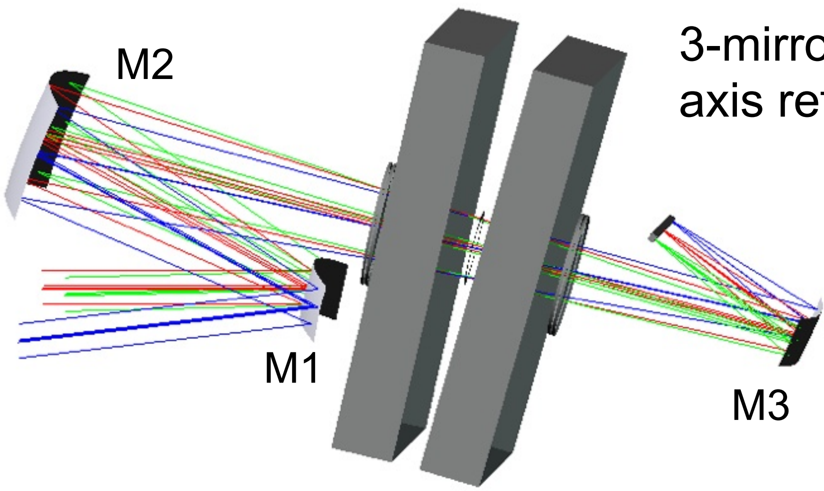


JPL MSPI2 (UV/VNIR) and MSPI3 (UV/VNIR/SWIR) detectors [10, 15 μm pixels]



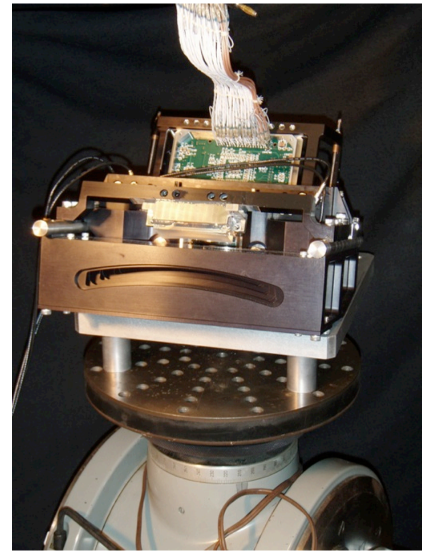
Teledyne CHROMA detectors (UV/VNIR and SWIR) [30 μm pixels]

Integration of the technologies into working cameras



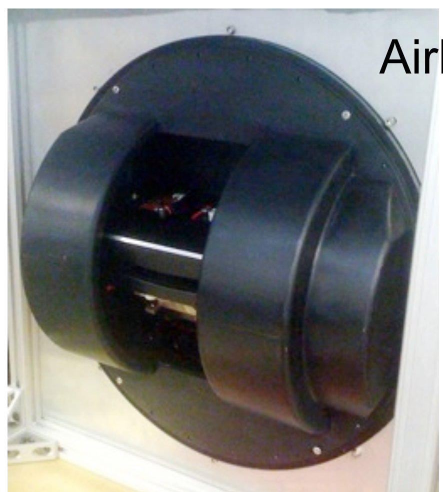
3-mirror f/5.6 off-axis reflector

Retardance modulator
= ¼ wave retarders + dual PEM



GroundMSPI

AirMSPI

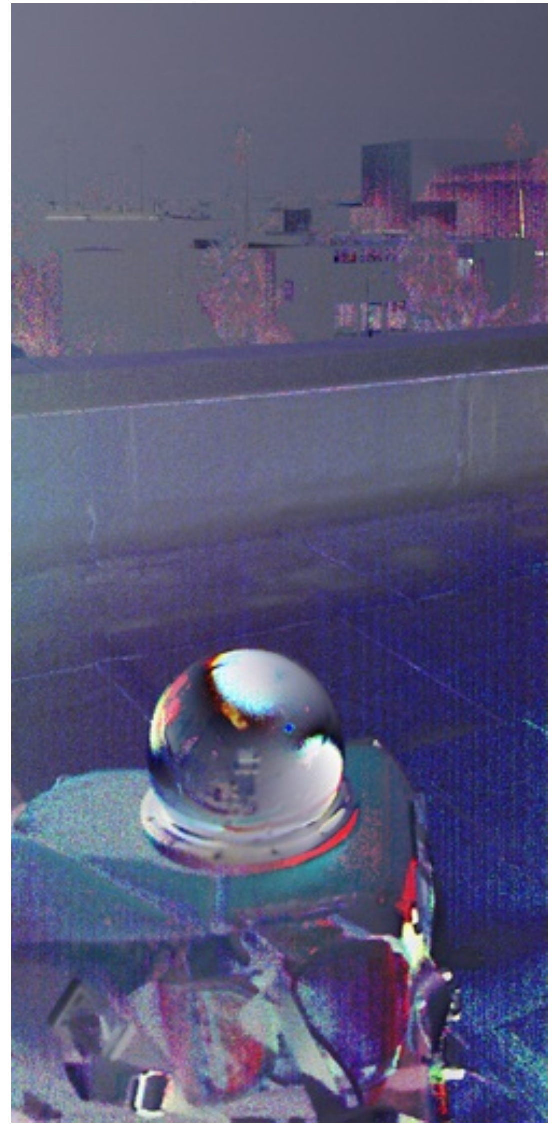


Spectral bands: 355, 380, 445, 470*, 555, 660*, 865*, 935 nm (*polarimetric)

Example GroundMSPI imagery

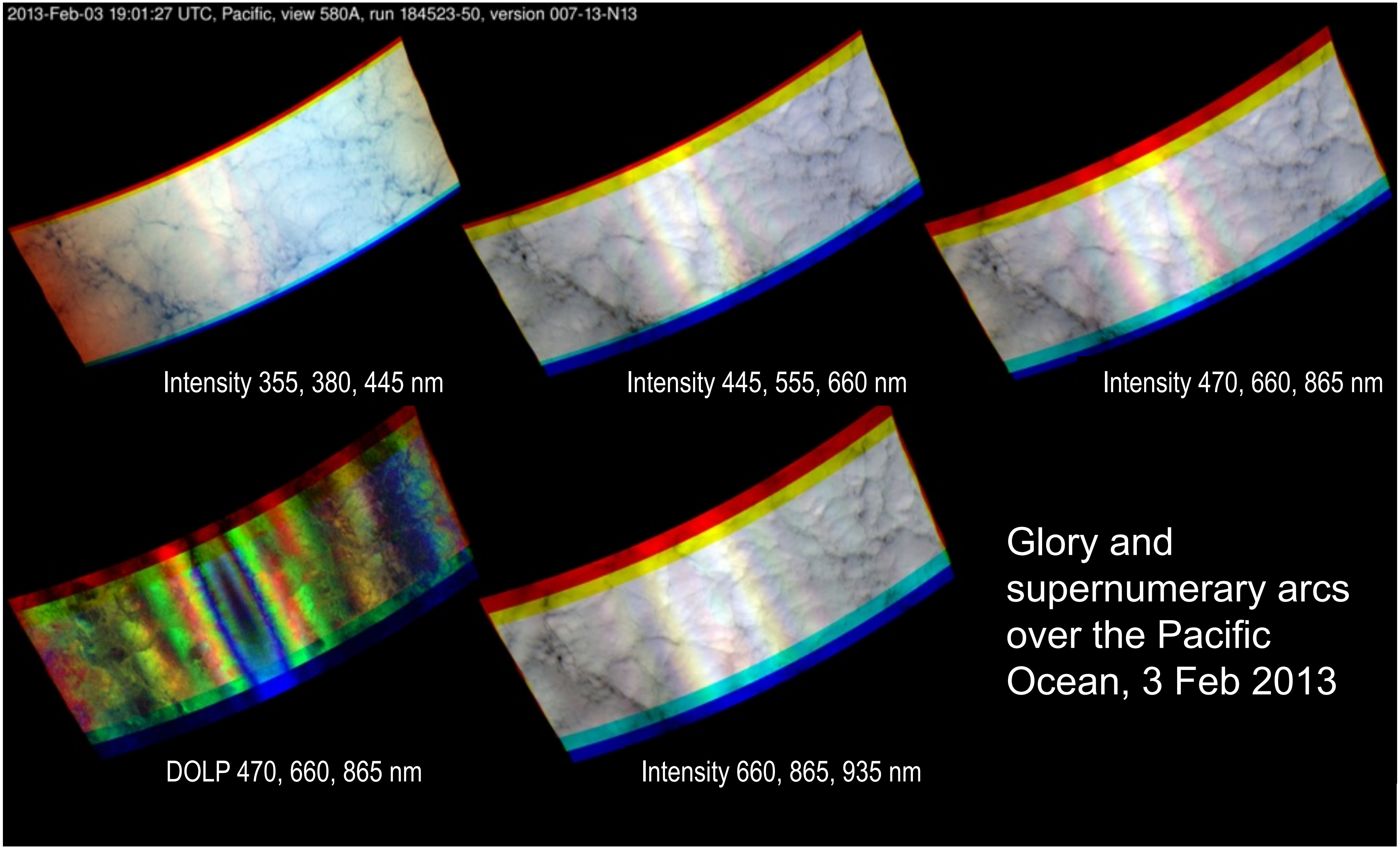
470, 660, 865 nm
Intensity

470, 660, 865 nm
DOLP



470, 660, 865 nm
AOLP

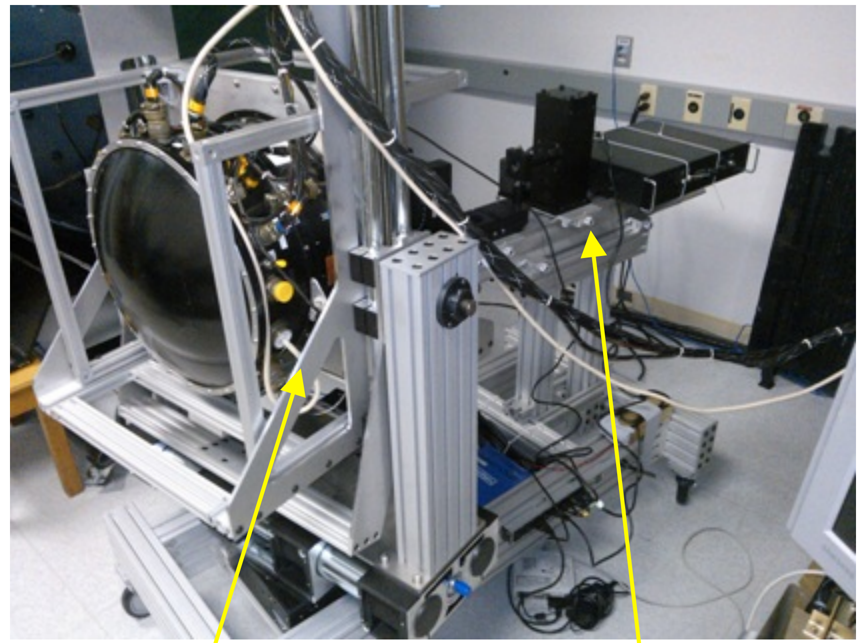
Example AirMSPI imagery



AirMSPI polarimetric calibration approach

- Rotating high extinction polarizer illuminates camera with known DOLP (100%) and variable orientation angle χ ($0^{\circ} \rightarrow 360^{\circ}$)
  - $q = Q/I = \cos 2\chi$, $u = U/I = \sin 2\chi$
  - Polarization aberrations in the camera cause linear crosstalk between *I*, *Q*, and *U*
  - A set of 10 calibration coefficients are derived from these data
  - Results are validated using partially polarized light generated using tilted glass plates

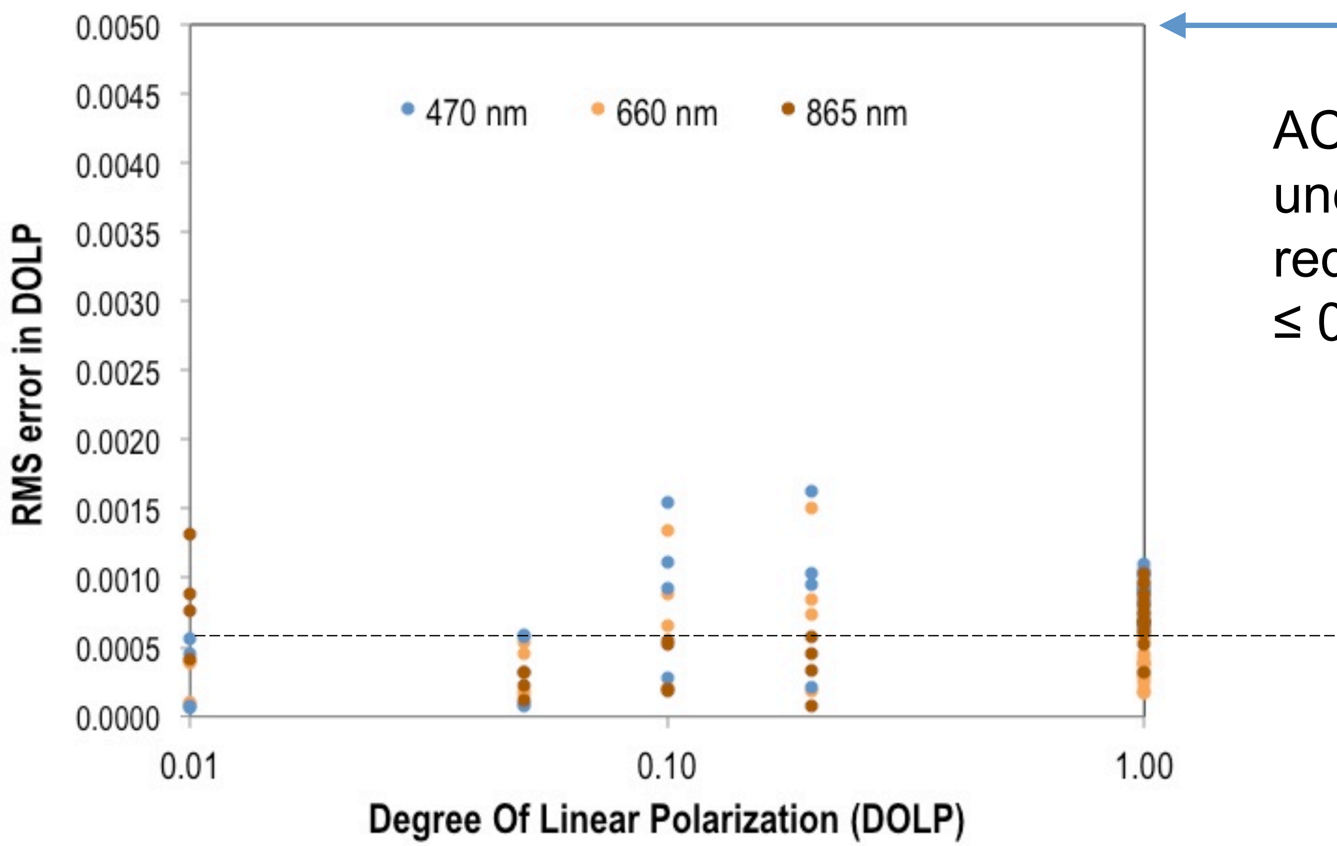
Polarization State Generator (PSG)



AirMSPI mounted on automated stage

PSG mounted on fixed rail

AirMSPI polarimetric calibration results



ACE DOLP uncertainty requirement: ≤ 0.005

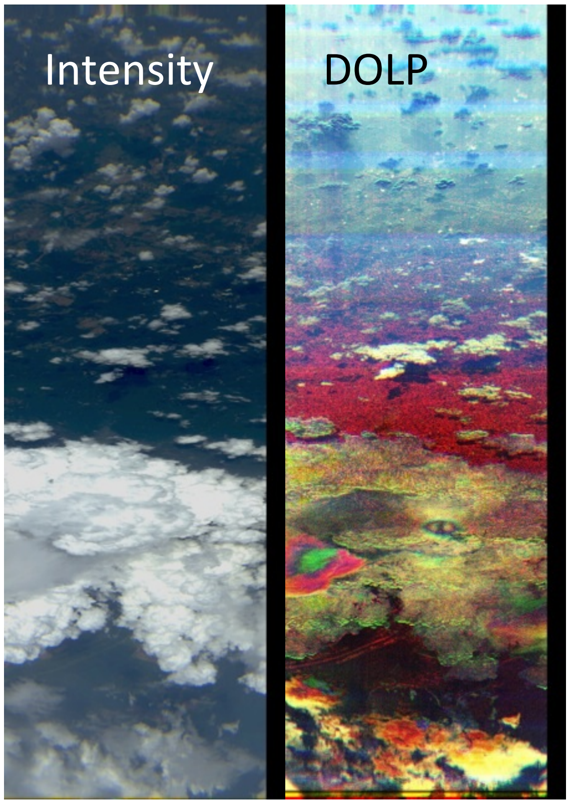
Median error = 0.0006

DOLP of 0.01, 0.05, 0.10, and 0.20 measured for polarizer angles 0º, 45º, 90º, 135º

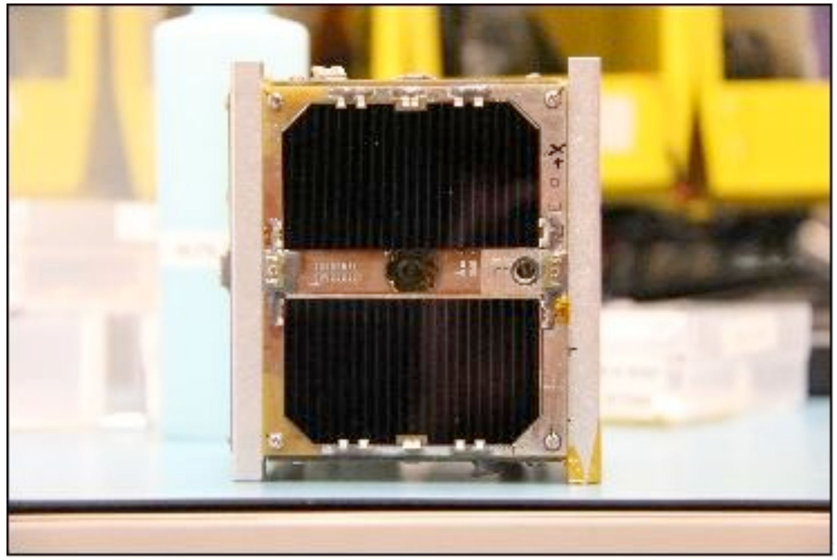
DOLP of 1.0 measured for polarizer angles from 0 - 170º in 10º steps

MSPI on-board processing (OBP)

AirMSPI quicklooks from SEAC^{4}RS



Reduction of the PEM modulation samples to *I*, *Q*, and *U* requires onboard processing to reduce data rate



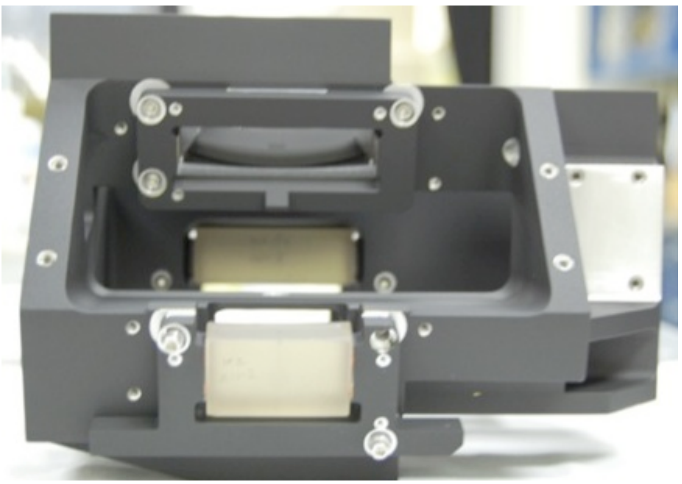
Michigan Multipurpose Minisat-2 with JPL COVE-2 payload

CubeSat On-board processing Validation Experiment-2 (COVE-2) carries the MSPI onboard processing algorithm and is the first spaceborne application of a new radiation-hardened Virtex-5QV Field Programmable Gate Array

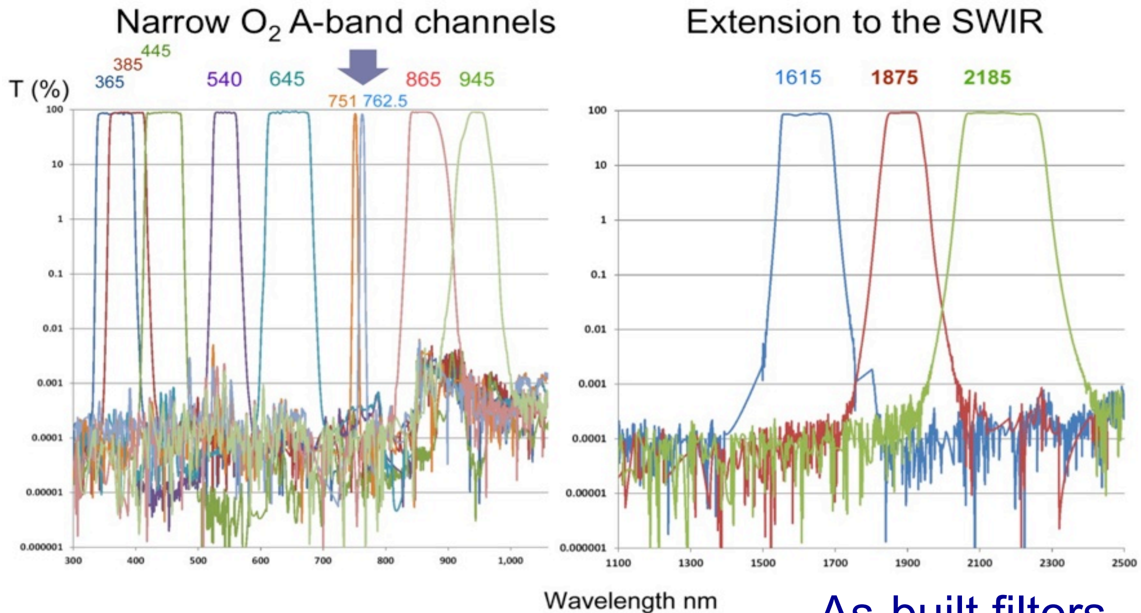
COVE-2 was launched 6 December 2013 and telemetry received 13 December demonstrated successful processing

Acknowledgment: P. Pingree, D. Bekker, T. Werne (JPL)

Second generation instrument (AirMSPI-2) is being built

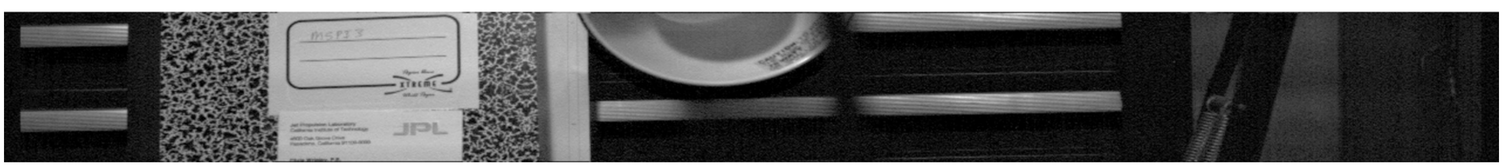


Optical bench and mirrors



As-built filters

12 spectral bands: 367, 386, 445*, 543, 645*, 751, 762.5, 862*, 945, 1620*, 1888, 2185* nm (*polarimetric)



Visible array image

Shortwave infrared array image

Technology Readiness Level (TRL) assessment

Technology	Maturation steps	Programs	Current TRL
PEMs	Vibration tested, life tested, thermally cycled In-flight control system demonstrated	IIP-04, AITT, PODEX, SEAC[4]RS	5
Achromatic quarter wave retarders	Developed and tested for VNIR operation, extended to SWIR, thermally cycled and vibration tested	IIP-04,-07,-10, OCO-3, AITT, PODEX, SEAC[4]RS	5
Stripe filters and patterned polarizers	Demonstrated on AirMSPI Extended to SWIR for AirMSPI-2, thermally cycled	IIP-04,-07,-10, AITT, PODEX, SEAC[4]RS	5
Readout integrated circuits and detectors	UV/VNIR flown on AirMSPI UV/VNIR/SWIR built for AirMSPI-2, thermally cycled, radiation tested CHROMA environ. testing	IIP-04,-07,-10, AITT, PODEX, SEAC[4]RS, Teledyne in-house	4 (MSPI3) 6 (CHROMA)
Rad-hard FPGA	Demonstrated in Earth orbit	AIST, COVE-2	7

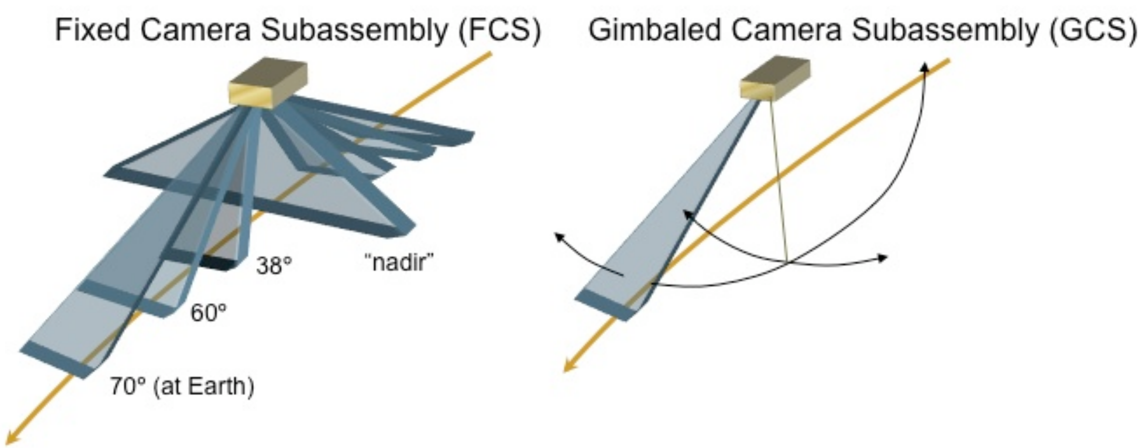
TRL 5 = System/subsystem/component validation in relevant environment

Technology maturation to TRL 6*

*System/subsystem model or prototyping demonstration in a relevant end-to-end environment

Subsystem	Approach	Status
Retardance modulator	Flight on AirMSPI-2 will demonstrate functional performance in the full visible - SWIR spectral range in an operational environment similar as to be encountered in LEO (vacuum, temperature 22º ± 2ºC)	Planned for Fall 2014
	Vibration, shock, and thermal survivability testing of the full modulator (PEMs, QWPs, optical probe) will complete subsystem qualification to TRL 6	TBD
Focal plane	Flight on AirMSPI-2 will demonstrate functional performance over the full visible - SWIR spectral range in an operational environment similar as to be encountered in LEO	Planned for Fall 2014
	Performance, thermal cycling, vibration, and radiation testing of the integrated detectors and filters will complete subsystem qualification to TRL 6	TBD

Strawman MSPI conceptual layout for ACE



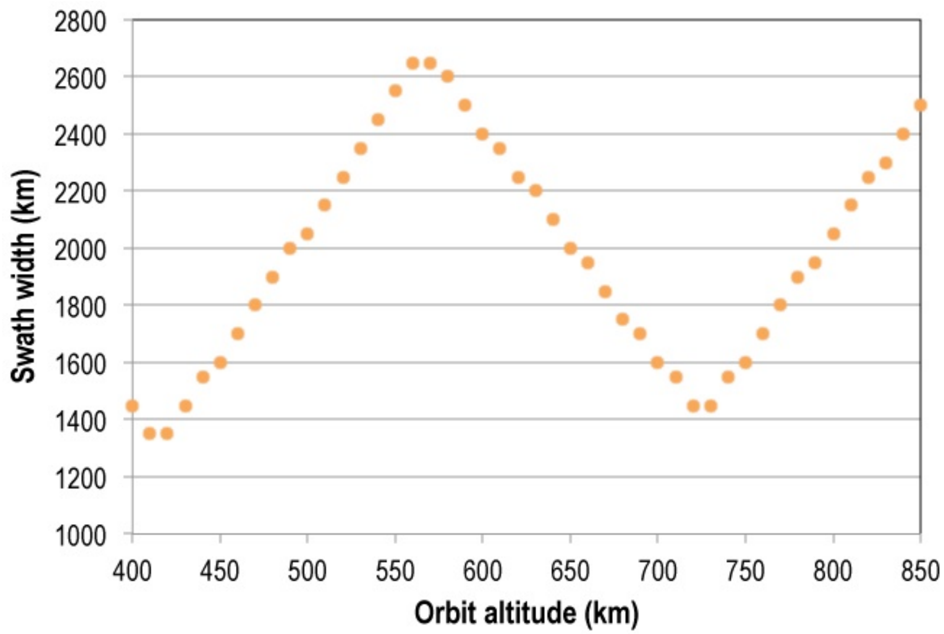
Fixed cameras

- 2-day coverage for nadir view
- Narrower swath for off-nadir views

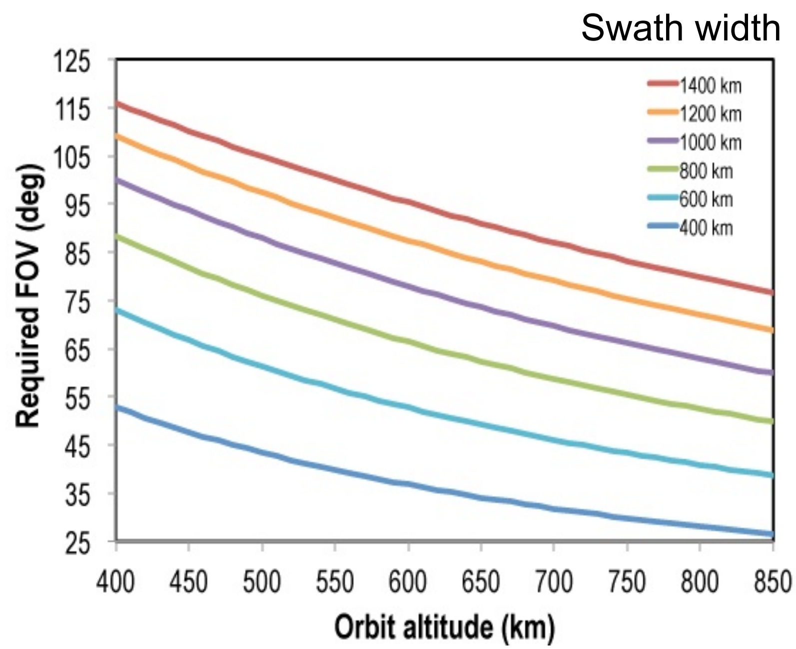
Gimbaled-camera (2-axis)

- High angular density sweeps
- Access to targets of opportunity
- Camera cross-calibration

Swath and FOV requirements vs. orbit altitude



Swath width required for global coverage in 2 days



Field of view required for various swath widths* (*current ACE off-nadir requirement is 400 km)

Acknowledgments

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